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CARBON STOCK AND CO_2 SEQUESTRATION RATE IN LINEARLY PLANTED *Vachellia nilotica* FARM TREES

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Climate is changing around the globe due to increased concentration of carbon dioxide (CO_2) in the atmosphere. *Vachellia nilotica* (L.) P.J.H. Hurter & Mabb., commonly known as babul, based agroforestry systems have the great potential to sequester the atmospheric carbon dioxide in both plant parts and soil, thus can perform a vital role in mitigating climate change. The objective of this study was to quantify the role of linearly planted *V. nilotica* farm trees in C sequestration. Keeping in the view the major study objective, linearly planted *V. nilotica* farmlands located in district Faisalabad were selected. Carbon stock and sequestration along with growth and biomass were assessed in four different aged linearly planted *V. nilotica* farm trees under semi-arid conditions. The soil organic carbon (SOC) was measured at two depths: 0-15 cm and 15-30 cm. The maximum diameter at breast height (DBH) and height was observed in 8 years old trees as compared to 4 and 6 years old trees. Plant biomass increased with age and maximum biomass (14.91 t ha^{-1}) was estimated at 8 years of age. Aboveground carbon stock and CO_2 sequestration increased from 0.72 t ha^{-1}and 2.66 t ha^{-1} at 2 years to 7.17 t ha^{-1} and 26.27 t ha^{-1} at 8 years of trees. The amount of SOC tended to be lower with depth but increased with tree age and ranged from 14.24 t ha^{-1} to 24.32 t ha^{-1} in surface soil (0-15cm) and 13.52 t ha^{-1} to 21.48 t ha^{-1}in subsoil (15-30 cm). The ecosystem carbon stock (plant + soil) varied from 37.23 t ha^{-1} at 2 years to 91.98 t ha^{-1} at 8 years of age. The above findings indicated that planting *V. nilotica* along the boundaries of farm crops not only capture carbon to mitigate climate change but also provide long term accumulation of biomass.
Keywords: Agroforestry, babul, biomass, soil carbon, climate change, tree measurements

INTRODUCTION

The continued increase in concentrations of so-called greenhouse gases (GHGs) because of anthropogenic emissions has resulted in substantial climate changes (Dhyani *et al*., 2016). The phenomena of global warming and climate change are largely attributed to the rapid increase of atmospheric CO_2 concentrations across the globe (Reddy *et al*., 2010). The higher CO_2 in the atmosphere is because of the difference between the C emission rates and rates at which sinks remove CO_2 from the atmosphere (Wang *et al*., 2014). This increased concentration of CO_2 can be reduced by lowering the energy demand or by enhancing the CO_2 removal from atmosphere through carbon sequestration (Reddy *et al*., 2010). The greater global warming risks due to this greenhouse gas emission has urged the researchers to identify a reservoir with high carbon capturing ability as an alternative climate change mitigation approach of terrestrial carbon sequestration (Sharma *et al*., 2011).

Among all anthropogenic sources, agriculture is contributing about 10-12% of GHGs emissions throughout the world (Smith *et al*., 2008). However, agricultural practices are best known for their role in sequestering greater amount of carbon both in vegetation and soil (Arora and Chaudhry, 2017). The combination of trees with crops (agroforestry) is a well-recognized and documented climate mitigation option around the globe due to its higher carbon sequestering ability (UNFCCC, 1997; Watson *et al*., 2000; Updegraff *et al*., 2004). Agroforestry has been practiced around the world and is among the oldest land use systems, in which trees are planted along farm crops on the same land unit (Nair *et al*., 2009; Raj *et al*., 2014). Recently, agroforestry systems have been recognized as a potential source to mitigate the harmful climatic conditions by sequestering greater amount of carbon than plantations (Ajit *et al.*, 2016). For example, agrisilvihorticulture system is sequestering about 93 t C ha^{-1} in Indian Himalayas (Yadav *et al*., 2019). Similarly, agrisilviculture systems in humid tropics of Southeast Asia are capturing about 12–228 t C ha^{-1} (Yadav *et al*., 2016) whereas in Africa carbon sequestered by different agroforestry land use systems were 51 to 448 t C ha^{-1} (Bajigo *et al*., 2015).

Despite emitting very less amount of CO_2, Pakistan is among the top ten climate change vulnerable countries in the world

(Kreft *et al*., 2017; Yasin *et al*., 2018). Agroforestry has got greater recognition as climate change mitigation option by sequestering carbon in many developing countries including Pakistan. In Pakistan, agroforestry provides numerous benefits to rural communities such as timber, fuelwood, fodder, food and income to overcome poverty, thus playing a remarkable role in their daily life (Nawaz *et al*., 2016; Farooq *et al*., 2017). Moreover, with the passage of time, agroforestry is receiving notable concerns by various government organizations, policymakers as well as by researchers for its carbon capturing capacity**,** economic benefits to alleviate poverty of rural farmers (Rahman *et al*., 2008; DAC, 2014).

Vachellia nilotica, earlier known as *Acacia nilotica* (L.) Willd. ex Delile, is a truly multipurpose tree, traditionally planted along farm crops in Pakistan. The area under *V. nilotica* is supposed to be increased by many folds as the species is cultivated on a variety of lands to overcome the shortage of fuel and timber around the globe, especially, in developing nations (Raj *et al*., 2015). Along with nitrogen fixing ability, the plant is also considered as source of tannins, gums, timber, fuelwood, fodder and medicine. Therefore, due to its greater economic importance, higher compatibility with crops and huge carbon sequestering capability, the species has got greater recognition and adaptability by the rural communities of the world (Qureshi, 2005; Singh *et al*., 2013). The functioning, productivity, structure, economic benefits and carbon stocks of acacia species, particularly of *V. nilotica*, in sub-continent have been predicted and documented by a number of researchers in compact forest plantations (Kaur *et al*., 2002; Raj *et al*., 2015; Hiloidhari*et al*., 2016; Balasubramanian *et al*., 2018). However, limited information on linearly planted *V. nilotica* based agroforestry systems is available under semiarid conditions. Furthermore, the biomass accumulation, carbon capturing and CO_2 sequestration rate of linearly planted *V. nilotica* based agroforestry systems under local climatic conditions have not been documented in Pakistan yet. Keeping the significance of issue, the study was designed to explore the role of different aged linearly planted *V. nilotica* trees in carbon capturing and CO_2 mitigation. The present study was carried out in District Faisalabad (Tandlianwala), with the main target of precise estimation of carbon distribution in both above and belowground portions of four different age classes of linearly planted *V. nilotica*.

MATERIALS AND METHODS

***Study area*:** The present study was conducted in Tandlianwala a sub division (Tehsil) of District Faisalabad, Pakistan (Fig. 1). The total area of the tehsil is about 490 square miles. Tandlianwala tehsil is surrounded by Faisalabad on the North, Okara on the east, Sahiwal on the south and Samundri on the west. River Ravi passes about 9 km in the east and it is the main source of irrigation for cultivated land. The area experiences climate extremes in summer as well as in winter. The summer season is very long and lasted from April to October with the mean temperature ranges between 39 °C to 27 °C while winters are short and severe with the mean temperature values of 17 °C and 6 °C. There is virtually no rainfall all year long in Tandlianwala. Most of the precipitation here falls in July, averaging 99 mm and the difference of precipitation between the driest and wettest months may reach up to 96 mm.

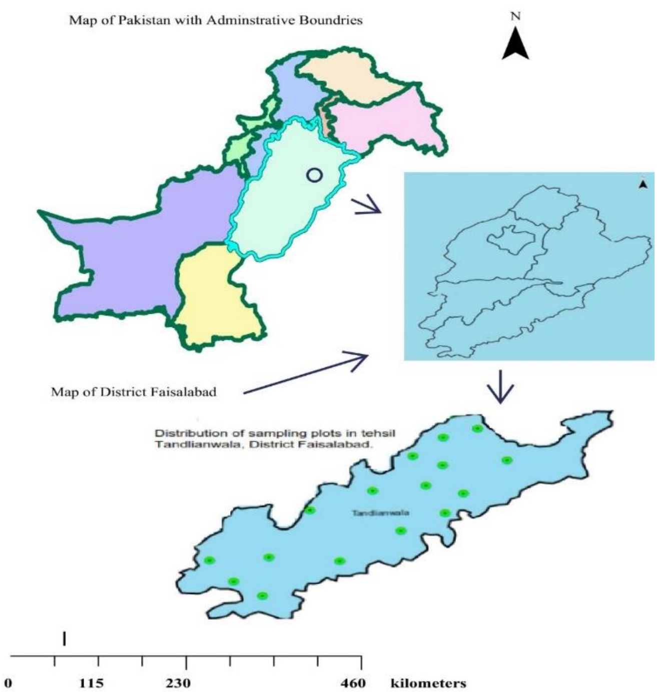

Figure 1. Map showing the administrative boundaries of Pakistan and distribution of sampling plots in tehsil Tandlianwala, District Faisalabad.

***Biomass, Carbon and CO_2 sequestration estimation*:** An inventory of *V. nilotica* trees was made in rural areas of tehsil Tandlianwala during August to October 2016. Field visits were carried out in 16 randomly selected villages of the area. Two sample plots each of size 0.405 ha (1 acre) from each village were randomly selected for each age class having linearly planted *V. nilotica* trees along farm crops, as described in details elsewhere (Nawaz *et al*., 2018; Yasin *et al*., 2018). The digital caliper was used to measure the diameter at breast height (DBH, in cm) while height was taken with Haga Altimeter initially in feet, which was then converted to SI units for each individual tree. The total number of *V. nilotica* trees of each age class was counted in all selected plots to determine the tree density. Carbon stored in woody biomass was estimated by non-destructive method. Above and belowground tree biomass was measured by using the species specific allometeric equations formulated by Rawat *et al*. (2008):

$$AGB\ (t\ ha^{-1}) = \text{Log } Y = -1.0646+0.9098\times \log D^2H$$
$$BGB\ (t\ ha^{-1}) = \text{Log} Y = -1.3952+0.8253\times \log D^2H$$

Carbon content of each age class was measured by considering 48.1% of tree dry mass as carbon (Thomas and Martin, 2012). The CO_2 sequestered by each age class was then computed by the procedure adapted by Afzal and Aqeela (2013).

Soil Carbon Estimation**:** The soil sampling procedure was adapted from Nawaz *et al*. (2016). Soil samples were collected manually with the graduated auger. For each age class, the samples were taken randomly under the tree canopy in cardinal directions and a composite sample was prepared. Overall 40 composite samples, 10 for each age class, 5 for each depth were collected. The samples were then immediately transported from field to Ayub Agricultural Research Center, Faisalabad within 12 hours where they were air dried. Soil Bulk density and organic carbon percentage was measured by the procedures documented by Arora *et al*. (2014) and Walkley and Black (1934). The soil organic carbon per hectare was calculated by multiplying the depth with the values of bulk density and organic carbon percentage (Joa Carlos *et al*., 2001).

Statistical Analysis**:** The collected data were analyzed using SAS 9.4 for windows. One-way ANOVA followed by Least Significant Difference (LSD) test was used to compare the difference biomass and carbon storage distribution in plant as well as in soil among four age classes of linearly planted *V. nilotica* trees.

RESULTS

Plant growth, Biomass and Carbon Concentration**:** Plant growth parameters showed an increasing pattern with age. The diameter at breast height (DBH cm) and height (m) of the plant was increased steadily and reached its maximum (24.27 cm and 11.88 m), respectively at the age of 8 years (Table 1). The incremental rate of growth parameters decreased with age and it was greater throughout the early growth years (2-4), as compared to 6 and 8 years. The relationship between tree age, DBH and height (r = 0.93, r = 0.89, p <0.001) was significant and indicated that the both incremental parameters were playing an important role in biomass accumulation of *V. nilotica* trees. Higher biomass content was estimated in stem portion of linearly planted *V. nilotica* as compared to the other parts among all age classes. The aboveground, belowground plant biomass accumulation was viewed in the order: 8>6>4>2 (Fig. 2).

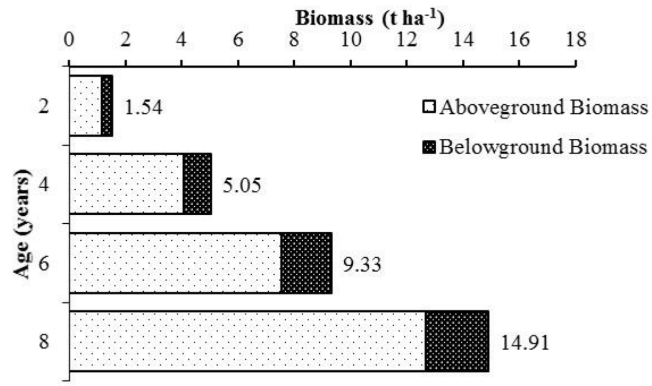

Figure 2. Biomass (above and below) production (t ha^{-1}) of four age classes of linearly planted *Vachellia nilotica*.

In the whole study region, the total plant biomass of *V. nilotica* trees was in the range of 1.51 t ha^{-1} to 14.91 t ha^{-1} with the greater accumulation in the 6-8 years plots as given in Table 2. The total plant carbon stock, CO_2 sequestration and

Table 1. The general status of growth parameters of four age classes of linearly planted *Vachellia nilotica* (mean ± S.D.).

Tree age(years)	Density (ha^{-1})	DBH (cm)	Height (m)
2	51±5.21^{a}	9.35±1.40^{c}	5.22±0.63^{d}
4	31±2.87^{b}	16.98±1.48^{b}	8.45±1.29^{c}
6	23±3.11^{c}	21.92±1.97^{ab}	9.15±1.35^{b}
8	21±1.42^{c}	24.27±3.20^{a}	11.88±1.73^{a}

Note:DBH: Diameter at breast height. Means with different letters are significantly different at 5% probability level. (One-way ANOVA and LSD test).

Table 2. Status of plant biomass, carbon stock, CO_2 sequestration and CO_2 sequestration rate ha^{-1}yr^{-1} of four age classes of linearly planted *Vachellia nilotica* (t ha^{-1}, mean ± S.D.).

Tree age(years)	Total Plant Biomass, Carbon, CO_2 Seq. & CO_2 Seq. Rate			
	TPB	**TPC**	**CO_2 Seq.**	**CO_2 Seq. rate**
2	1.51±0.68^{d}	0.72±0.33^{d}	2.66±1.19^{d}	0.88±0.40^{c}
4	5.06±2.53^{c}	2.43±1.22^{c}	8.93±4.46^{c}	1.48±0.74^{b}
6	9.34±1.98^{b}	4.49±0.95^{b}	16.45±3.49^{b}	2.05±0.44^{a}
8	14.91±5.59^{a}	7.17±2.69^{a}	26.27±9.84^{a}	2.38±0.89^{a}

Note:TPB: Total Plant Biomass, TPC: Total Plant Carbon, CO_2 Seq.: CO_2 Sequestration and CO_2 Seq. rate: CO_2 Sequestration rate ha^{-1}yr^{-1}. Means with different letters are significantly different at 5% probability level. (One-way ANOVA and LSD test).

CO_2 sequestration rate showed an increasing trend with the increase of age. The mean content of total plant carbon, CO_2 sequestration and sequestration rate varied from 0.72 t ha^{-1}, 2.68 t ha^{-1}, 0.88 t ha^{-1} yr^{-1} at the 2 years of age to 7.17 t ha^{-1}, 26.27 t ha^{-1} and 2.38 t ha^{-1} yr^{-1}, respectively at the 8-year-old trees (Fig. 3).

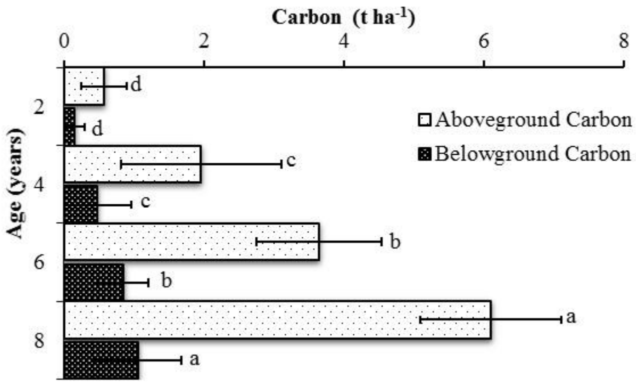

Figure 3. Carbon (above and below) production (t ha^{-1}) of four age classes of linearly planted *Vachellia nilotica*.

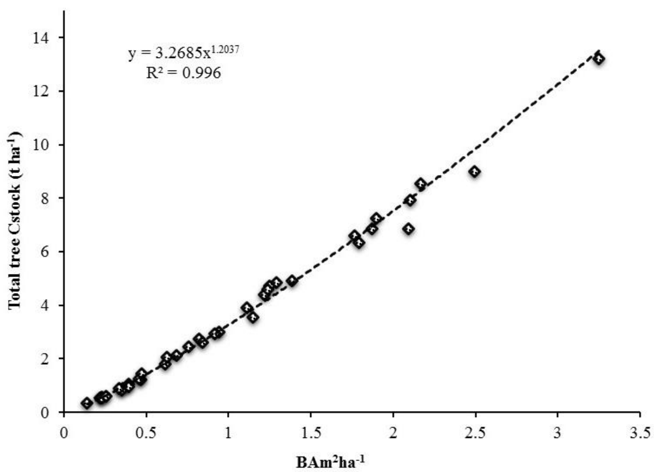

Figure 4. Relationship between tree basal area (m^2 ha^{-1}) and total tree carbon stock (t ha^{-1}) for inventory plots of four age classes of linearly planted *Vachellia nilotica*.

The total tree basal area per plot and total tree carbon stock per plot showed a positive and significant linear relationship (R^2 = 0.99, p <0.001) as depicted in Figure 4, along with a significant correlation between tree age and total carbon tree carbon stock (r = 0.87, p <0.001) for the complete inventory plots.

***Soil Carbon*:** Higher soil organic carbon (SOC) was estimated in the 0-15 cm soil as compared to 15-30 cm soil. A significant difference in soil organic carbon was noticed due to age with the maximum values in 8 years plots and minimum values in 2 years plots at both depths (Table 3). On the other hand, a decreasing trend of organic carbon% and soil organic carbon was observed with soil depth for entire age classes. Soil bulk density increased with the soil depth and exhibited antagonistic results with tree age. The values of soil bulk density showed a decreasing trend with the tree age and were ranged from 1.48 g cm^{-3} to 1.34 g cm^{-3}for 0-15 cm depth and 1.54 g cm^{-3} to 1.46 g cm^{-3} for 15-30 cm depth for all age groups. In the 0-15 cm soil, soil organic carbon increased distinctly and ranged from 14.24 t ha^{-1} in the 2 years plots to 24.32 t ha^{-1} in the 8 years plots with a percent increase of 70.78%. Soil organic carbon increased maximum 58.87% in the 8 years plots, followed by 30.17% in the 6 years plots and 15.97% in the 4 years plots at 15-30 cm depth. The correlation between SOC and tree age at both depths was highly significant (r = 0.87, r =0.82, p <0.001).

***Ecosystem Carbon Stock*:** The ecosystem carbon stock of linearly planted *V. nilotica* consists of two pools: biomass carbon and soil carbon. Majority of the plant carbon content was accumulated in aboveground portion especially stem. Both plant and soil carbon pools increased with the increase of age. Total plant carbon storage in four age classes of linearly planted *V. nilotica* at plot level ranged from 9.47 t ha^{-1} at the 2 years of age to 46.18 t ha^{-1} at the 8 years of age. Similarly, among all age classes, the highest soil carbon was computed for 8 years and lowest for 2 years *V. nilotica* trees at both depths, with soil organic carbon markedly increased from 2 years plots to 8 years plots. The total carbon storage in linearly planted *V. nilotica* ecosystem was in the order of 37.23 t ha^{-1}> 58.43 t ha^{-1}> 70.28 t ha^{-1}>91.98 t ha^{-1} for 2, 4, 6 and 8 years plots, respectively (Table 4).

Table 3. Effect of four age classes of linearly planted *Vachellia nilotica* on OC (%), BD (g cm^3) and SOC stock (t ha^{-1}).

Age (years)	OC %		BD (g cm^{-3})		SOC (t ha^{-1})	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
2	0.64±0.02^d	0.58±0.01^d	1.48±0.02^a	1.54±0.02^a	14.24±0.5^d	13.52±0.4^d
4	0.80±0.01^c	0.69±0.02^c	1.43±0.02^b	1.53±0.01^a	17.23±0.7^c	15.68±0.6^c
6	0.99±0.01^b	0.79±0.02^b	1.39±0.01^c	1.49±0.03^b	20.84±0.6^b	17.60±0.6^b
8	1.21±0.02^a	0.98±0.03^a	1.34±0.03^d	1.46±0.03^c	24.32±0.4^a	21.48±0.5^a

Note: OC= Organic Carbon, BD= Bulk Density & SOC= Soil Organic Carbon. n=5, Means with different letters are significantly different at 5% probability level. (One-way ANOVA and LSD test).

Table 4. Ecosystem carbon sequestration (t ha^{-1}) in four age classes of linearly planted *Vachellia nilotica*.

Age (years)	Ecosystem Carbon Stock (t ha^{-1})		
	TPC	SOC(0-15 cm + 15-30cm)	TC
2	9.47	27.76	37.23
4	25.52	32.91	58.43
6	31.84	38.44	70.28
8	46.18	45.80	91.98

Note: TPC, SOC and TC refers to Total Plant carbon, Soil organic carbon and Total carbon

DISCUSSION

***Biomass and Growth Parameters*:** The biomass and tree growth in linearly planted *V. nilotica* along farm crops increased remarkably with age. The mean annual increment of plant growth parameters such as DBH and height also increased but slowed with an increase in age. These findings support the hypothesis that *V. nilotica* biomass and growth increased remarkably in both above and belowground portion of the trees with an increase of age. The baseline biomass productivity at the age level was lowest for 2 years (1.51 t ha^{-1}) and highest (14.91 t ha^{-1}) for 8 years of age. The high value of biomass for 8 years was due to the superior DBH as compared to other three age classes. This sort of tree growth and biomass accumulation in different linearly planted agroforestry trees had documented in a number of previous studies in *Eucalyptus camaldulensis* (Kanime *et al*., 2013; Nawaz *et al*., 2017b) in *Populus deltoides* (Yasin *et al*., 2018), in *Faidherbia albida* (Marone *et al*., 2017), and in *Acacia nilotica* and *Dalbegia sissoo* (Kaur *et al*., 2002). Moreover, higher biomass accumulation was noticed at early stages and it slowed down with an increased age. The findings of this study indicated that the maximum biomass was accumulated in the 4-6 years old trees (Table 1). These findings were similar with other studies, which explained higher biomass accumulation in both above and belowground tree components (Yadava, 2010; Arora *et al*., 2013). However, the total biomass estimated of the current study was much lesser than the estimates of Rizvi *et al*. (2011) for *P. deltoides*, Lodhiyal and Lodhiyal (2003) for *D. sissoo* and Harmand *et al*. (2004) for 6 years old *Senna siamea*. This difference of biomass among various tree species might be attributed to several factors such as age, number of trees ha^{-1}, site quality, location, management practices, planting technique and system and environmental conditions of the area (Goswami *et al*., 2013; Balasubramanian *et al*., 2018; Nawaz *et al*., 2018).

***Carbon Stock and CO_2 Sequestration rate*:** The ample amount of carbon can be stored in tree based agroforestry systems, both in above and belowground perennial components. Generally, the 45 to 50% of tree dry weight is taken as carbon content (Wang and Feng, 1995; Rizvi *et al*., 2011). In this study, above and belowground carbon along with CO_2 sequestration rate has been quantified in four different age classes of linearly planted *V. nilotica* agroforestry system. The whole study area has a carbon stock (above + belowground) in the range of 9.47 t ha^{-1} to 46.18 t ha^{-1}. These results were highly consistent to the findings of Yasin *et al*. (2018) for *Populus deltoides* bund planted agroforestry system (43.45 t ha^{-1}), Arora and Chaudhry (2017) for *A. nilotica* + *D. sissoo* (41.44 t ha^{-1}), Zebek and Prescott (2006) for *P. deltoides* (51.2 t ha^{-1}) and Sundarapandian *et al*. (2013) for *Leucaena leucophloea* and *A. nilotica* (33.9 t ha^{-1} to 58.99 t ha^{-1}) planted in tropical region of India. However, the observed values were reasonably lower than 62.5 t ha^{-1}, 72 t ha^{-1} as described by Chauhan *et al*. (2010) and Fang *et al*. (2007) for *P. deltoides*. Moreover, the maximum amount of carbon reported by Kaur *et al*. (2002) in a silvopastoral system (*A. nilotica* + grasses) was only 18.55 t ha^{-1}, much lower when compared to current findings. The high variations of carbon contents among different tree species might be because of difference in mean annual increment and fast growth rate along with age, tree density and quality of planting stock (Gera, 2012). Nair *et al*. (2009) stated that higher carbon stock not always refers to greater carbon sequestration rate as it depends on various factors like species, land use type and cultural practices. Carbon stock and carbon sequestration are totally different terms as carbon stock refers to net amount of carbon present at inventory time while carbon sequestration is a procedure through which atmospheric carbon is removed and deposited in a carbon pool (Takimoto *et al*., 2008). In agroforestry, majority of tree species are planted for short rotation by the farmers. Harvesting of these trees after regular intervals results in loss of carbon but when the harvested wood is converted into poles, packaging materials, plywood and furniture manufacturing, carbon is again stored (Arora, 2014). The CO_2 sequestration rate of 2 to 8 years old *V. nilotica* varied from 0.88 t ha^{-1} yr^{-1} to 2.38 t ha^{-1} yr^{-1}, respectively. These estimations are comparatively lesser than the findings reported by Kaul *et al*. (2010) for *P. deltoides* (8 t ha^{-1} yr^{-1}), Lal and Singh (2000) for plantations (3.2 t ha^{-1} yr^{-1}) but slightly higher when compared with moderate (teak) and slow growing (sal) tree species (2 t ha^{-1} yr^{-1} and 1 t ha^{-1} yr^{-1}), respectively.

***Soil Carbon*:** Soil is an important subsystem in the atmosphere CO_2 mitigation especially in terrestrial ecosystem. Many researchers had also revealed the significance of agroforestry systems as soil carbon pool (Huang *et al*., 2012; Nawaz *et al*., 2017a). Among different land used types, forests along with agroforests and plantations stock higher soil carbon as compared to crops (Kaushal *et al*., 2012). The findings of the present study regarding soil organic carbon supports the hypothesis that soil organic carbon contents increased with the increase of tree age. Total soil organic carbon ranged from 27.76 t ha^{-1} at 2 years to 45.8 t ha^{-1} at 8 years at both depths. Moreover, higher percentage of organic carbon and soil organic carbon stock was accounted for surface soil (0-15 cm). This could be explained by fact that higher accumulation of tree litter at surface soil results in greater carbon input (Kaushal *et al*., 2012). Davis *et al*. (2003) observed an increase of soil organic carbon (29.8 t ha^{-1} to 42 t ha^{-1}) in mineral soil i.e. 0-10 cm with the increase of stand age. The results about soil organic carbon storage were similar to *P. deltoids* based bund planted agroforestry systems as described by Yasin *et al*. (2018). Results of Arora and Chaudhary (2017) for *A. nilotica* and *D. sissoo* and Arora *et al*. (2014) for *P. deltoides* plantations were much consistent to our findings.

Conclusion**:** For the formulation of better management strategies, to understand the sway of trees on farm lands, especially, linear plantations and how these effects may be influenced by environmental change is of prime importance. The current study was conducted to measure the approximate carbon stocks of four different age classes of linearly planted *V. nilotica* trees. The present study indicated that the linearly planted *V. nilotica* trees (2-8 years old) had the greater ability to accrue higher amounts of biomass and carbon when compared to bund planted or other agroforestry systems. The substantial amount of carbon and CO_2 sequestered by *V. nilotica*, make it the best choice for farmers to earn some additional income in terms of the carbon market. The findings of this study suggests that planting *V. nilotica* species along farm crops is a sustainable option to mitigate climate change by sequestering large amount of carbon from the atmosphere. Moreover, to understand the role of these agroforestry systems in climate change mitigation and national carbon budget, scientifically solid and exact tree biomass and carbon stock should be computed at provincial level.

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